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Sandia Wind Program FY94 Annual Operating Plan

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SANDIA WIND PROGRAM
FY94 ANNUAL OPERATING PLAN

Supporting the
WIND ENERGY TECHNOLOGY PROGRAM

for the
WIND/HYDRO/OCEAN DIVISION
OFFICE OF RENEWABLE ENERGY CONVERSION
ENERGY EFFICIENCY AND RENEWABLE ENERGY
DEPARTMENT OF ENERGY

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ABSTRACT

This document presents the objectives, accomplishments and activity plan for the Sandia Wind Energy Technology Program. The status of the current program is summarized and the planned FY94 activities are defined. Appendices detailing the cost, performance and schedule associated with these activities are also included. Funding requirements are given for several scenarios in order to reflect the impact of funding variability on program progress.

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I. INTRODUCTION

For twenty years Sandia National Laboratories has played a key role in what is now the Department of Energy's wind energy program. Starting with a 1973 informal working relationship with Canada's National Research Council, we began with aerodynamic analyses of the performance of a Darrieus or Vertical Axis Wind Turbine (VAWT). During the ensuing decade, our efforts expanded to include all engineering aspects of VAWTs and led to the commercialization of this concept, including the installation of over 500 units in California that continue to operate successfully today.

During the next decade, we witnessed a dramatic decline in federal wind program funding followed by a re-emergence of wind as the leading contender for a commercially viable, utility-scale renewable energy generation source. Throughout this cycle Sandia not only maintained the role of lead lab for VAWT technology, we actually broadened our roles to include specific engineering problems being encountered by Horizontal Axis Wind Turbines (HAWTs) as well. The fundamental principle guiding all our wind technology involvements continues to be to provide any national service that can benefit from our laboratory core capabilities - in this case engineering science competencies. Specifically, our competencies in aerodynamics, structural dynamics, materials, fatigue, controls, testing and systems engineering form the basis for all of our efforts.

As a multipurpose DOE National Laboratory, Sandia provides a unique breadth and depth of technical capabilities. These capabilities are supported by multiple funding sources both within the DOE and by other government agencies. This fact provides a tremendous leveraging effect so that a greater variety of analytical tools and experimental hardware can be brought to bear on any specific problem. For the Wind Energy Technology Program within DOE/EE, the magnitude of the leveraging for the past several years has been approximately 40:1. This means that capabilities have been provided to the Wind Program that might otherwise have been too expensive to develop from a single funding source. An additional aspect of Sandia's value to the wind program is the unique financial support provided by U.S. industry. Under formal Work-for-Others agreements Sandia has received or is receiving nearly $400k in direct, private funding to provide technical services (both analytical and experimental) to the wind industry. It should also be noted that other DOE/EE entities are providing leveraging effects in the Technology Assistance area through the Sandia Design Assistance Center, where a relatively small wind investment ($100k or less historically) taps into a multimillion dollar program for international and small/hybrid applications.

This FY94 Annual Operating Plan (AOP) presents the Sandia program by objectives and goals in Section II, followed by accomplishments and plans in Section III. In order to better quantify the associated costs, performance goals and schedules, Appendices A-C cover these three items, respectively. The individual tasks (described in Appendix B) will combine to produce an output that will enable Sandia to achieve the overall objectives stated below. Appendix C contains summary milestone charts for the program tasks and indicates the multiyear aspect of the Sandia effort. Finally, Appendix D lists recent publications to quantify progress achieved toward program objectives.

II. PROGRAM OBJECTIVES AND GOALS

The objectives of the Wind Energy Technology program at Sandia are twofold. First, we develop design techniques, predictive models and experimental procedures that can be used directly by industry to produce economically viable, long-life wind energy systems. Second, we conduct longer-term research efforts, the benefits of which are less certain and less apt to be realized in the immediate future.

Utilizing an engineering systems approach, Sandia is a focal point for DOE-designated government, industry and university research and development as well as for efforts to transfer newly developed technology to U.S. companies through workshops, Sandia-sponsored seminars, participation in conferences, and, most importantly, industry joint participation arrangements.

Sandia VAWT program goals in the early 1980s were to establish technical feasibility through in-house R&D and then to assist in demonstrating economic viability through joint industry efforts. These goals were in general highly successful, but it became clear that additional technological improvements were required to achieve true commercial viability. As a result of this requirement our primary VAWT-related goals became: 1) quantify, through both analytical and field/experimental means, the performance and costs associated with the next generation of technological improvements; and 2) actively pursue a new initiative to transfer this technology to U.S. industry. Successful first phase testing on the DOE/Sandia VAWT Test Bed provided unique performance quantification, while ongoing cooperative efforts with the U.S. company FloWind are providing improved cost data and serving to transfer Sandia-developed technology to industry.

Our more recent HAWT program goals are: 1) develop a greater understanding of, and the requisite tools needed to analyze, unsteady aerodynamics, structural response, component fatigue life, and operation and control of wind turbines; and 2) assist U.S. industry in the successful development of next generation machines that will be economically competitive in the mid-1990's and beyond. To this end, we participate as appropriate in any DOE effort in technology applications and/or advanced wind turbine programs.

Whether for HAWT or VAWT technologies, the scope of the Sandia efforts encompasses applied research and technology development in the areas of fluid mechanics, solid mechanics, control theory and power engineering. These efforts span the two key areas of the DOE Wind Program; i.e., I. Applied Research and II. Utility and Industry Programs. An essential aspect of these efforts is the fully integrated approach that we bring to bear on the important issues facing wind technology development in this country. Every element required for a complete evaluation of turbine performance is included: turbulent wind models, unsteady (often nonlinear) aerodynamic loads, steady-state and transient structural responses, control strategies and effects, resultant component fatigue life evaluations (including materials and manufacturing considerations) and power quality aspects for grid-connected applications. It is only through this all-inclusive approach that the interrelationships can be fully understood and quantified. Once we have obtained this understanding, the final, crucial step is its application to develop a reliable, manufacturable, economic turbine. This application clearly requires close, cooperative working relationships with U.S. industry. Finally, these relationships provide inputs to an additional objective: to determine additional applied research needs and directions so that all aspects of the DOE program are properly focused on current and future industry requirements.

III. PROGRAM ACCOMPLISHMENTS/FY94 PLANS

A. APPLIED RESEARCH

1. Aerodynamics

The airfoils of wind turbines undergo large and/or rapid angle-of-attack oscillations in very complex unsteady flow fields. We must be able to model the interaction of airfoils with these flow fields in order to understand this phenomenon and design more efficient and reliable wind energy conversion systems. The fluid physics that govern the unsteady aerodynamic loads must be better understood before we can develop this model.

The simplest aerodynamic loads/performance models are blade element models for HAWTs and double-pass multiple-streamtube models for VAWTs. This class of code equates the momentum lost by the wind when it passes through the turbine with the energy extracted by the turbine blades. We in the U.S. wind-energy community have developed the capability to model, in an approximate manner, the tip loss and finite aspect ratio of HAWTs and the unsteady aspects of WECS aerodynamics, including dynamic stall, pitching blade sections, apparent mass effects, blade-wake interactions, and turbulent atmospheric winds. Recent studies of stochastic-wind induced aerodynamic loads have provided valuable insight into possible reasons for the observed much-shorter-than-predicted WECS fatigue life.

Taken collectively, these models form a reasonable basis for initially estimating the aerodynamic performance of current and future WECS systems with clean blades, even though additional work is needed to improve accuracy in the dynamic stall and pitching blade representations and to determine the effects of flow three-dimensionality.

In the real world, however, the blades on a WECS system quickly become contaminated with bug debris and other types of roughness. This roughness reduces WECS performance and has a major economic impact on the operation of a wind farm. Most wind-farm operators wash their blades on a regular basis, in spite of the high costs involved, to keep their machine performance as high as possible. The degree of performance degradation and the frequency with which the blades must be washed are dependent upon the specific blade profile used, and must be determined from turbine operating experience.

Computational Fluid Dynamics. The loads/performance codes mentioned above are based on the assumptions of quasi-steady aerodynamic phenomena and have been modified to incorporate approximate representations of unsteady phenomena such as dynamic stall and stall hysteresis that have been observed on both HAWTs and VAWTs. Although the accuracy of these codes has been consistent with the accuracy of stochastic wind models and structural response modes in the past, those wind and structural models have recently become increasingly more accurate, and the aerodynamic loads/performance codes now may well be the limiting factor in accurate fatigue life prediction for WECS. We have begun an effort to bring the recent major advances in the field of Computational Fluid Dynamics (CFD) to bear on the modeling of flow fields in the vicinity of an operating WECS. CFD, which involves solution of the governing Navier-Stokes equations (including unsteady effects) throughout the flow field, is extremely computationally expensive. However, as a research tool, CFD (together with experimental measurements) will be very useful in helping us characterize flow phenomena in many areas of the WECS flow field. With this improved knowledge, we will be able to develop more accurate, but still approximate, aerodynamic analysis codes for use on PC or workstation computers. This effort draws heavily on the extensive investment that Sandia has made in CFD in recent years for application to other areas.

In FY93, we obtained a steady-state CFD solution (lift and drag coefficients in good agreement with experimental data) for the SAND 18/50 airfoil shape at 4^{o} angle of attack. Our failure to obtain a steady-state solution for an 8^{o} angle of attack case indicates that the flow is not steady - a time-dependent solution is required. The CFD code was modified as necessary to permit an unsteady solution.

Our CFD work for the first part of the year will focus on developing an unsteady solution capability for our current F3D code and obtaining unsteady solutions for the SAND 18/50 airfoil with separated flow. We will also be looking at other CFD codes that might be better suited for our efforts, with the goal of identifying one or two that have the best potential and starting to use those. In addition, we will be working with Professor Bill Wentz at Wichita State and with industry to analyze proposed aileron configurations to help guide their work and to compare predictions with actual flow field measurements.

Unsteady Aerodynamics. We have developed a finite difference potential flow model which utilizes sources and sinks to efficiently represent the three-dimensional viscous flow field around any number of wind turbines (VAWTs or HAWTs) arbitrarily located in a wind farm. While this modeling approach does not yield a high degree of accuracy on the local scale, it does allow us to quantify multiple turbine-to-turbine interactions and investigate the effects of terrain features and incident wind characteristics. Modifications to enable the code to model complex terrain and include atmospheric turbulence effects were completed in FY93. Both FloWind Corporation (VAWTs) and R. Lynette & Associates (HAWTs) funded Dr. Rajagopalan of Iowa State University in FY93 to utilize this model in studies for them.

Other funding sources at Sandia are supporting work on a fast vortex solver that promises to yield an order of magnitude decrease in the solution time of vortex-based codes. We will investigate the possibility of using that solver to speed up the

VDART3 VAWT aerodynamic performance code and make the development of a panel version of the 3-D code to improve accuracy feasible.

The accuracy of all of our aerodynamic performance codes depends very heavily on the accuracy with which dynamic stall can be modeled. The incorporation of an improved dynamic stall model such as the Beddos/Lieschmann model, validated against the unsteady airfoil data we have obtained in the Ohio State wind tunnels, will be a high priority item.

Dr. Rajagopalan's wind farm model will be extended to include an eddy viscosity turbulence model this year. In addition, we will be comparing turbine performance predictions from his code with predictions from the SLICEIT and VDART3 codes to validate his code or identify areas of disagreement and quantify the extent of the disagreement.

Blade Roughness Effects. While the observed effect of bug debris on virtually all WECS rotors has been a significant decrease (20% or more) in the maximum power output, testing of the SAND 0018/50 blades on the Test Bed showed that the maximum power output is increased by 15-20 percent as the result of bug-debris accumulation. Wind-tunnel tests on the SAND 0018/50 airfoils at the Ohio State University utilizing standard grit roughness have shown that the presence of roughness results in increased drag, with little change in lift. These results are inconsistent with the observed increase in turbine maximum power. This raises the question of whether the grit roughness used in the wind-tunnel tests accurately simulates the actual bug debris roughness.

Sandia has developed a prototype of a non-contact surface measuring device that will enable us to accurately characterize the bug debris found on WECS blades in the field. This device became operational in FY93 and has been used to measure the grit roughness used to simulate blade roughness in the Ohio State University wind-tunnel testing of airfoils. This roughness is significantly different in size and character from the roughness that has been measured on the 34-m Test Bed blade.

At this time we have no analytical or experimental methods (short of building new blades and flying them on turbines) for analyzing the effects of bug debris buildup on blade performance. Data obtained with the Spider will be used to develop an empirical model that will be incorporated into an airfoil design code to enable us to analytically investigate the effects of roughness on proposed airfoils during the design process.

In conjunction with NREL and the USDA, we hosted a meeting of industry, lab, and academic personnel at NREL in April of this year to consider the importance and economic impact of the WECS blade-surface roughness issue. The meeting participants unanimously agreed that the blade surface roughness is a critical issue with a large economic impact on wind-turbine operators, and a coordinated plan to address that issue is needed. An outline of such a plan has been prepared and distributed to meeting participants and DOE headquarters staff.

The 8' X 10' Ohio State University wind tunnel will be used to carefully investigate the manner in which surface roughness modifies the airfoil boundary layer to cause the observed changes in airfoil performance. Changes in the boundary layer characteristics due to the presence of roughness will give us insights into the flow mechanisms involved. Improved understanding of the underlying fluid mechanics of this flow will ultimately enable us to design airfoils that are less sensitive to roughness than any airfoils that are now available.

The knowledge gained from this test will be supplemented by additional data on actual wind-turbine blade surface roughness obtained with the Spider surface mapper. This data, obtained in a cooperative effort with wind-industry partners, will tell us how that roughness varies with blade shape, blade rotational speed, blade geographical location, and season of the year. It will also guide us in developing new wind-tunnel testing techniques that will better define the sensitivity of airfoils to field-type roughness.

2. Structural Response

<u>Structural Analysis</u>. We have had substantial success developing finite element models of wind turbine structures, illustrated by the completion of the HAWTDYN transient analysis of HAWTs, TRES4 random vibration capability that predicts steady state but random response of VAWTs operating in the presence of turbulence, and VAWT-SDS the VAWT Structural Dynamics Simulator tool for analysis turbulence, advanced controls, variable speed operation, and flexible structures. A similar capability for HAWTs is desperately needed to enable designers to evaluate advanced turbine designs. In FY92 we began to examine the applicability of VAWT structural dynamic analysis techniques to HAWT structures. Several synergistic applications were discovered, and a plan for finite-element analysis of HAWTs has been mapped out and presented to both NREL and industry. At the same time, NREL has initiated contracts to make the commercial dynamics analysis package ADAMS able to conduct HAWT structural dynamic analysis. We discovered that using existing Sandia capabilities in an area where NREL is attempting to create its own capability is defined as duplication of effort on the part of Sandia. Efforts are now under way to assist NREL in whatever way possible to create HAWT structural dynamics simulation software that is accessible to industry.

<u>System Identification Techniques</u>. The uncertain material and structural properties of the composite materials used in many wind turbine blades makes structural modeling difficult. A method of determining detailed structural properties using modal tests is in progress. There are three potential applications: (1) validation of computer models, (2) damage detection (also known as field

inspection, or health monitoring), and (3) manufacturing quality control (or factory inspection). This effort builds on capabilities created under past vibration analysis and suppression work (namely the NExT code) and is highly leveraged by Sandia internal R&D funding in this area. Cooperative fatigue tests of industry supplied hardware will enable us to evaluate the more promising techniques for field application in the next few years.

Reliability. Structural reliability analysis is a way to evaluate the effects of uncertainty and inherent randomness on the performance (especially the fatigue life) of a wind turbine structure. The results of the reliability analysis include the relative importance of uncertain variables as well as sensitivities of the reliability to design parameters. The FAROW code (Fatigue and Reliability of Wind Turbines), completed and introduced through an industry short course in FY93, is being refined to provide an accessible tool for wind turbine designers and developers. FAROW produces measures of the success of individual components of the wind turbine system. FAROW has already shown the sensitivity of wind turbine fatigue to the "tails" of stress cycle distributions. Additional study in this area is planned for this year. This year we also will begin to examine ways to provide tools for the industry to assess the reliability of the entire system, with individual component reliabilities as inputs. The ultimate goal of this work is to create system reliability tools tailored to wind turbine applications that can be used by designers and developers in economic forecasting of design and implementation options.

3. Fatigue and Materials

Advanced Fatigue Models. The operational experiences of the wind industry in California have shown that WECS components (primarily blades) were failing at unexpectedly high rates. This realization led to the development and distribution to industry of the LIFE code, a damage accumulation model for VAWT components, in the late 1980s. A generalized numerical framework (the LIFE2 code) for the fatigue and/or fracture analysis of WECS components has been completed. Currently, the LIFE2 code is being evaluated by several U.S. wind turbine companies, wind farm operators, consultants and researchers. To further assist the U.S. wind turbine community in the use of this code, a short course on its use was presented in the summer of 1993. In FY94, the LIFE2 code will continue to be updated. The updates will be based on the suggestions received from its users. Additional short courses are not anticipated at this time; however, if requested, they will be taught. Sandia staff will continue to consult with the users of the code.

Composites Fatigue. The prediction of service lifetimes requires a detailed understanding of the fatigue characteristics of WECS materials. In FY93, the characterization of the composite materials in high cycle fatigue has proceeded with Montana State University (MSU) as a major subcontractor. They have developed a small-coupon testing technique to speed test times. Samples, from several major

U.S. blade manufactures, are being tested and the results reported on a regular basis. During this Fiscal Year the fatigue testing of composite materials will continue with the testing of additional materials from U.S. blade manufacturers. Current characterizations will be expanded and constitutive equations suitable for inclusion in the LIFE2, and other fatigue analyses, will be developed. This program is being conducted in coordination with the NREL full-blade and blade component fatigue testing program.

__Joint Bonding Research.__ Additional characterization studies are also being conducted at Sandia on bonded joints. These studies use existing finite element analyses and fatigue tests to characterize the fatigue behavior of bonded joints in fiberglass composite materials. This year the studies centered on the bending fatigue of steel inserts bonded to typical WECS fiberglass composites. With the completion of the initial test series, the experimental study is being developed around typical U. S. blade materials. The bond test program has now developed an industrial partner. This year, this program will concentrate on the analysis of an industrial joint. Fatigue loading of this joint will be used to validate the techniques used in this analysis.

__Non-Destructive Testing/Inspection.__ The failures of turbine components also can be traced, in part, to poor quality control of the blade manufacturing process. To identify poorly manufactured blades and to inspect used blades for accumulated damage in the WECS manufacturing environment requires the use and adaptation of commercially available wide-area Non-Destructive Testing (NDT) techniques to inspect large WECS components quickly. In FY93, we reported on the use of acoustic emissions and coherent optical techniques to follow damage accumulation in a full blade under quasi-static loading to failure. This proof-of-concept test was conducted with NREL in their full-blade test facility. Both techniques demonstrated the capability to inspect a whole blade and to find manufacturing flaws and areas of damage. The acoustic emission techniques were also used this year on the full-blade fatigue test of the U.S. Windpower blade. This test was conducted under the auspices of the NREL CRADA with U.S. Windpower. The NDT program will continue in FY94 with the analysis of the data from the U.S. Windpower blade test and will report those results. An industrial partner is being developed for this program to provide samples for evaluating the NDT techniques on actual wind turbine blade components. After laboratory testing, one or more NDT techniques will be taken into a manufacturing environment for evaluation. This program has a direct tie at Sandia to the FAA Aging Aircraft Program.

4. Advanced Components/Controls

__Controls.__ A computer code, entitled ASYM, has been developed that is a design analysis tool that is currently being used to determine the effect of different control algorithms on fatigue lifetime. In this code, the relative effectiveness of control algorithms is measured using a "norm" that is based on a present-value calculation for the energy produced by the machine over its lifetime. The model has been modified to permit analysis of more general control algorithms and variable-speed operation, including the ability to quickly pass through resonance zones within the turbine operating range. Initially the 34m VAWT Test Bed located in Bushland was the basis for the turbine model used in the code. Recently a new version of the code that uses a 15m Danish HAWT as the turbine model was developed for use by industry.

A wind simulator has also been developed that is capable of simulating high frequency wind data for long durations of time. This is important for control simulations and other simulators that require high frequency wind data for input. Typically, control simulators need to simulate for long durations, up to a year, in order to thoroughly test and compare control algorithms. High frequency field data are rarely available for this length of time and it is usually not practical to collect and transfer the data between computers. Hence, an algorithm that is capable of accurately simulating high frequency wind data becomes important. The wind simulator uses an auto-regressive method to create the low frequency mean wind speeds. The mean wind speed is created to fit a Weibull distribution with an exponential auto-correlation function. High frequency data is then created in blocks using FFT methods, tapered and overlaid to make it continuous, and superimposed on the mean values. The algorithm is capable of simulating diurnal as well as seasonal effects with appropriate user defined statistics. The simulator also includes a wind direction option.

A computer code that is capable of simulating advance control concepts such as adaptive control and fuzzy logic control is currently being developed. The new code is entitled the Advanced Control Evaluation Simulator (ACES). Current research involving control theory considers steady-state and transient operations, variable-speed operations, and high-wind survivability, and is based on classical control logic. No capability exists to take into account individual machine performance variations or array subgroup variations in a windfarm. Such factors as siting effects (including farm-to-farm and local terrain variabilities) and array effects (including wakes and power depletion) can significantly impact machine performance. ACES will aid in the development of control algorithms that will take these factors into account by using advanced concepts such as adaptive control, expert systems, and fuzzy logic control. New advanced algorithms will be developed for supervisory control of wind farms as well as individual wind turbines to achieve smoother and more efficient operation.

B. UTILITY AND INDUSTRY PROGRAMS

1. Turbine Development

In FY93, FloWind Corporation continued a development program under contract to SNL per the "Government/Industry Wind Technology Applications Project" ["Letter of Interest" (LOI) Number RC-1-11101]. Their project is entitled "High Energy Rotor Development, Test and Evaluation." Its objective is to "develop, construct, test and evaluate a high energy rotor and related improvements..." for their 19-m VAWT. Effective with the July 31, 1993 invoice to SNL, FloWind has expended approximately $1,160K towards this contract. This expenditure represents FloWind's total estimated cost for this project, based on their initial proposal to SNL. SNL's obligation is limited to $370K in this cost-shared contract, of which approximately $365K has been released to FloWind. The remaining approximately $5K of this contract is being held by SNL until FloWind has completed this project and issued a final report. On numerous occasions, FloWind has stated that they are committed to finishing this contract with their own additional funding. And, SNL has been assured by FloWind that they have committed significant additional development funds to ensure the completion of this contract. The cost overruns for this program did not come as a total surprise to FloWind. They revealed, early on, that their estimated costs for this program were very low. However, they chose to continue along a design path leading to an optimum retrofit, rather than simply fulfilling the terms of their contract. The pultrusion of the blades for their retrofit turbine, the heart of their design optimization, has started. The prototype turbine is expected to see first turn in early CY 1994.

2. Cooperative Programs

In FY91 we entered into a cooperative activity, jointly funded by the DOE and FloWind, to evaluate the current status of the FloWind VAWT fleet and investigate options to improve the performance of those 512 machines. We provided relevant skills in aerodynamics, structural dynamics, fatigue, materials, controls and field testing to FloWind to aid them in their repair program and evaluate the performance of their existing machines. More importantly, we improved and transferred several of our analytical tools to them, and we provided our technical skills to help them in their investigations of the performance and reliability improvements that can potentially improve the cost effectiveness of the existing fleet. In FY93, we concluded our work with FloWind. We did a limited amount of analysis for them, transferred several analytical tools to them, transferred our structural-analysis technology to their consultant and helped him develop his own analysis capability, assisted in code validation of two structural codes, provided technical assistance to blade designers, and helped develop a detailed project plan. As a result of our efforts in this area, FloWind agreed to establish a follow-on Work for Others program that calls for FloWind to pay Sandia approximately

$150,000 over a two-year period for continued assistance in analysis and testing of wind turbines.

DOE initiatives to assist industry in upgrading existing turbines and developing advanced designs are the primary responsibility of NREL. Sandia has supported NREL through participation in the proposal evaluation process for a number of solicitations, including the Advanced Wind Turbine (AWT) program and the Wind Technology Applications/Letter of Interest (WTAP) program. Since Sandia has DOE program responsibility for VAWT technology, the contractual responsibility for the FloWind WTAP participation was transferred to us. Herb Sutherland administered this program throughout FY93.

We have no funding to conduct any cooperative work with FloWind in FY94, but we will continue to do some work for them under the new Work for Others agreement.

We will also continue to support NREL in the AWT and other DOE programs.

3. Technology Assistance

Wind Design Assistance. Sandia's Design Assistance Center (DAC) has been providing technical and educational assistance in international applications for renewable energy for a number of years. Until late FY92 funding was provided primarily through the DOE/EE Offices of Solar Energy Conversion and Technical Assistance, but beginning at that time the Wind/Hydro/Ocean Division began supporting this effort. International projects having potential for small wind electric systems were supported through resource assessment, site evaluation and training activities. The primary objective has been to fully integrate wind options into the overall Renewable Energy services, with geographic emphasis placed on Latin America and the Caribbean. During FY93 this effort focused successfully on possible applications involving small stand-alone systems as well as village electrification using hybrid concepts. During FY94 (assuming funding support) work will focus on conducting International RE Workshops, publishing of appropriate documents (including coordination of an International Wind Document) and identifying two RE projects that should include wind generation in the project energy mix.

APPENDIX A

Financial Status

APPENDIX A. SANDIA WIND PROGRAM FY94 AOP BUDGET

Task No. Task Description	FY94 Priority	FY93 Actual	Budget Scenarios A	B	C	Foot-Notes	Participants (TBD=To Be Determined)	App. B Page
Key Area I.: Applied Research								
Sub-Area 1.: Wind Characterization								
1.1.1 Turbulent Wind Models	N/A	0	0	0	0			N/A
Sub-Area 2.: Aerodynamics	**Sub-Area Total:**	**600**	**500**	**600**	**1100**			
1.2.1 Turbulence & Airfoil Response	11	190	100	200	200		SNL/Iowa St/Ohio St	1
1.2.2 Advanced Measurement Techniques	25	100	0	0	100		SNL/NREL	2
1.2.3 Computational Fluid Dynamics	3	150	300	300	300	(2)	SNL	3
1.2.4 Blade Roughness Effects	9	100	100	100	100	(2)	SNL/NREL/Ohio St/T	4
1.2.5 Unsteady Sensors/Adv. Airfoils	23	60	0	0	400		SNL/Ohio St	5
Sub-Area 3.: Structures & Fatigue	**Sub-Area Total:**	**1500**	**1400**	**1800**	**2800**			
1.3.1 WECS Structural Dynamics	6	400	200	200	500	(2)	SNL/NMERI/TBD	6
1.3.2 Structural Reliability	1	200	300	300	300	(2)	SNL/Stanford/TBD	7
1.3.3 Vibration Analysis & Suppression	22	150	0	0	300		SNL	8
1.3.4 Structural Parameter Estimation	8	50	200	200	200		SNL	9
1.3.5 Composite Microdesign/FEM	13	0	0	200	200	(2)	SNL/TBD	10
1.3.6 Advanced Fatigue Models	10	150	100	100	100	(1)	SNL/NMERI/12 Co's	11
1.3.7 Composites Fatigue	2	250	200	200	400	(1)	SNL/Montana St/USW/	12
1.3.8 Joint Bonding Research	7	150	200	200	200	(2)	SNL/TBD	13
1.3.9 Non-Destructive Testing/Inspection	5	150	200	400	600	(1)	SNL/NREL/USW et al	14 & 15
Sub-Area 4.: Advanced Components	**Sub-Area Total:**	**540**	**250**	**500**	**700**			
1.4.1 Windfarm Expert Systems	12	100	50	50	50	(1)	SNL/USW	16
1.4.2 WECS Advanced Controls	4	100	200	200	200	(2)	SNL/Vachon/TBD	17
1.4.3 Testing/Power Quality	15	230	0	100	100		SNL/NMERI/USDA	18
1.4.4 Fuzzy Control Applications	16	0	0	100	100	(2)	SNL/TBD	19
1.4.5 WECS System Performance	17	60	0	50	50		SNL/NREL	20
1.4.6 Forecasting/Controls	24	50	0	0	200	(2)	SNL/TBD	21
	Key Area Total:	**2640**	**2150**	**2900**	**4600**			
Key Area II.: Utility & Industry Programs								
Sub-Area 1.: Utility Integration	**Sub-Area Total:**	**0**	**0**	**0**	**200**			
2.1.1 Utility Industry Support	21	0	0	0	200	(2)		22
Sub-Area 2.: Turbine Development	**Sub-Area Total:**	**0**	**0**	**100**	**100**			
2.2.1 Wind Technology Applications Proj.	19	0	0	100	100		SNL/FloWind	23
Sub-Area 3.: Cooperative Programs	**Sub-Area Total:**	**160**	**0**	**200**	**1100**			
2.3.1 Advanced Manufacturing	20	0	0	0	900	(2)	SNL/Industry TBD	24
2.3.2 VAWT Product Improvement	18	160	0	200	200	(1)	SNL/FloWind	25
Sub-Area 4.: Technology Assistance	**Sub-Area Total:**	**100**	**0**	**100**	**200**			
2.4.1 Wind DAC	14	100	0	100	200	(1)	SNL-DAC	26
	Key Area Total:	**260**	**0**	**400**	**1600**			
	Expense Totals:	**2900**	**2150**	**3300**	**6200**			
	Capital Equipment:	0	0	0	300			
	GRAND TOTALS:	**2900**	**2150**	**3300**	**6500**			

Footnotes:
(1) = Current Collaboration With Industry
(2) = Proposed Collaboration With Industry

APPENDIX B

Task Summary Sheets

TASK 1.2.1: Turbulence & Airfoil Response **Priority = 11**

Principal Investigator: D. E. Berg

FY94 Funding (Scenarios A/B/C): $ 100/200/200k

Cumulative Funding (Thru FY93): $1560k

PROJECT SUMMARY

Background

A stochastic wind model has been developed and interfaced with a simplified aerodynamic loads code; results to date indicate that the stochastic wind can cause extreme variations in turbine cyclic loading. Tests on oscillating models have shown that the Gormont dynamic stall model is not very accurate for WECS use. A finite difference code capable of modeling the flow field around multiple wind turbines in a computationally efficient manner has been developed and demonstrated. The effect of simple terrain features on the flow field near a turbine has been investigated with this code.

Objectives

The objectives of this task are to develop and validate aerodynamic loads/performance models that accurately predict the detailed aerodynamic loads acting on WECS; develop simplified versions of these codes and adapt to PC use, if possible; and develop an accurate array model that can be used by industry and by researchers to study terrain, siting, array, and wake effects on turbine performance.

Approach

Multiple parallel efforts will be used to accomplish these objectives:

1. Continue development and modification of the existing aerodynamics performance/loads codes to incorporate improved dynamic stall models.
2. Determine aerodynamic characteristics of airfoils in the Ohio State University wind tunnel under simulated WECS operating conditions to provide additional data for dynamic stall models.
3. Enhance the existing array finite-difference model (FDM) by adding a turbulence model and the ability to evaluate the effect of terrain features (provided by digitized terrain data) and nearby turbines on turbine performance.
4. Validate the enhanced FDM code against test cases and available wake and array data available in the literature and from wind-farm operators.

Output

The output of this task will be a group of aerodynamics loads/performance models representing combinations of accuracy and computer runtime economy that can predict turbine rotor aerodynamic loading. In addition, we will have a validated array model that requires relatively large computer resources but which is capable of analyzing WECS array and wake effects and the impact of terrain on the performance of and flow field around wind turbines. This model promises to be a very viable siting tool for industry.

TASK 1.2.2: Advanced Measurement Techniques **Priority = 25**

Principal Investigator: D. E. Berg

FY94 Funding (Scenarios A/B/C): $ 0/0/100k

Cumulative Funding (Thru FY93): New Start

PROJECT SUMMARY

Background

Experiments at Sandia and NREL have shown that existing aerodynamic loads/performance codes apparently do not accurately predict the instantaneous aerodynamic loads acting on the blades of operating WECS. However, we do not yet understand why these codes fail. Since these loads (which result from the interaction of the unsteady flowfields and the WECS blades) drive the structural response, the fatigue life, and the COE of the turbines, we must improve our ability to predict them. We can accomplish this only through a more complete characterization of the complex, unsteady flowfields near WECS airfoils.

Objective

The objective of this task is to develop an accurate characterization of the flowfields in the immediate vicinity of the blades of operating WECS. This data will be used to guide the development of improved aerodynamic models and to validate those models.

Approach

This task comprises the following interdependent efforts:

1. Adapt and calibrate state-of-the-art instrumentation and techniques for flowfield characterization in wind-tunnel environments, pursuing cooperative efforts with U.S. industry where appropriate.
2. Characterize the flow in the immediate vicinity of two-dimensional oscillating airfoils in controlled and documented wind tunnel environments using this instrumentation and these techniques.
3. Perform field experiments on operating wind turbine rotors using this instrumentation and these techniques--in particular, surface shear stress and airfoil pressure distribution measurements.

This task will entail close cooperation with NREL to ensure coordination between this work and the NREL Comprehensive Experiment effort.

Output

This task will yield a much improved set of data detailing the characteristics of the flowfield in the near vicinity of the blades on operating WECS. This data will help guide the development of more accurate aerodynamic codes, which will result in cheaper, more reliable wind turbines.

TASK 1.2.3: Computational Fluid Dynamics **Priority = 3**

Principal Investigator: D. E. Berg

FY94 Funding (Scenarios A/B/C): $ 300/300/300k

Cumulative Funding (Thru FY93): $ 150k

PROJECT SUMMARY

__Background__
Current aerodynamic loads/performance codes incorporate approximate representations of unsteady phenomena such as dynamic stall and stall hysteresis that have been observed on WECS. Although this has been consistent with the accuracy of stochastic wind models and structural response models in the past, those other models have recently become increasingly more accurate, and the aerodynamic loads/performance codes now appear to be the limiting factor in accurate fatigue life prediction for wind turbines. Computational Fluid Dynamics techniques have been used to accurately model the flow about a 2-d airfoil in unstalled flow and a rotating 2-d turbine in laminar flow.

__Objectives__
The objectives of this task are to apply recent developments in computational fluid dynamics (CFD) to the modeling of the flowfields in the immediate vicinity of WECS, incorporating the effects of stochastic wind input and unsteady aerodynamics such as dynamic stall, and to use CFD techniques to augment industry and research wind-tunnel studies of WECS blades and performance control devices such as aerilons and flaps.

__Approach__
This task draws heavily on the existing SNL and Ecole PolyTecnique investment in CFD expertise to maximize the results that are obtained. It comprises the following efforts:

1. Use an existing general-purpose CFD code to analyze the flow over a static, two-dimensional airfoil, with and without separated flow, to demonstrate feasibility.
2. Model the flow around 2-dimensional pitching airfoils undergoing deep stall, and validate the results against existing experimental data from the Ohio State University tests.
3. Analyze the performance of conceptual blade profiles and flow-control devices over the entire range of WECS operation, and validate the results against wind-tunnel data.
4. Model 3-dimensional WECS, and validate the code results against detailed loads and performance data from the NREL and SNL experimental turbines.
5. Incorporate a turbulence model in the Ecole model, expand it to full 3-d modeling, and validate the results against experimental data.

__Output__
The results of this task will be validated WECS-specific unsteady aerodynamic loads and performance codes, requiring a mainframe computer or workstation for execution. One code will be tailored to perform analyses of blades and control devices for industry and laboratory application. The other code will model full WECS turbines. This code will serve as a benchmark against which simplified codes, capable of running on PCs or workstations, can be evaluated, and will provide guidance on needed alterations to existing PC/workstation-based aerodynamics codes.

TASK 1.2.4: Blade Roughness Effects **Priority = 9**

Principal Investigator: D. E. Berg

FY94 Funding (Scenarios A/B/C): $ 100/100/100k

Cumulative Funding (Thru FY93): $ 100k

PROJECT SUMMARY

Background

The sensitivity of WECS blade performance to surface roughness effects, including bug debris build-up, has a large economic impact on wind-farm operations, for both stall-regulated and pitch-regulated blades. First-generation, WECS specific blades designed by SNL and NREL exhibit reduced performance sensitivity to these roughness effects, but do not eliminate it. The sensitivity of these blades to actual field-type roughness has been determined only from actual field testing - we have no other proven method for determining sensitivity. In addition, wind-farm operators are in desperate need of inexpensive fixes for the tens of thousands of existing wind turbines.

Objectives

The objective of this task is to minimize the economic effects of surface roughness accumulation on existing and new-generation WECS blades.

Approach

This task entails the following efforts:

1. Investigate blade modifiers such as VG's, spoilers and boundary-layer trips for their potential in offsetting roughness effects on existing blades.
2. In a cooperative effort with the wind industry and USDA, measure surface roughness on a representative sample of operating wind turbine blades.
3. Utilize wind-tunnel tests to compare the effects of field-type roughness with the effects of grit-type roughness and develop a simulation roughness for field and wind-tunnel testing.
4. Compare these effects against those predicted by the PROFILE airfoil design code (using transition fixing options), and, if necessary, incorporate the ability to model this "bug" roughness into that code.

Close coordination with personnel from the wind industry, the USDA at Bushland, TX, Ohio State University, and NREL, all of whom are conducting or have conducted work on bug-debris roughness effects, will be maintained throughout this project.

Output

This task will result in:

1. Suggested blade modifications which may reduce roughness sensitivity of blades for existing WECS and significantly increase wind-farm revenue.
2. A detailed understanding of how bug debris accumulates on wind turbine blades and how that debris produces the observed roughness effects.
3. A standard testing technique which can be used in wind-tunnel and field tests to accurately evaluate the sensitivity of an airfoil to bug debris buildup.
4. Airfoil design codes that accurately predict surface roughness effects on airfoil performance.

TASK 1.2.5: Unsteady Flow Sensors/Advanced Airfoil Design **Priority = 23**

Principal Investigator: D. E. Berg

FY94 Funding (Scenarios A/B/C): $ 0/ 0/400k

Cumulative Funding (Thru FY93): $60k

PROJECT SUMMARY

Background

The WECS blade flow field data which has been obtained to date has been limited to surface pressure measurements and surface flow visualization (tufts and shear-stress sensitive coatings). Additional data on the flow field itself, data such as free-stream turbulence level and wake extent, turbulence level, and decay rate, are needed to guide new model development and for model validation. New types of instrumentation and instrumentation that has not previously been applied to this application will be required to obtain this information. Specifications on blade profile tolerance and blade surface finish are now quite arbitrary - no effort has been made to determine the effects on blade performance or blade roughness sensitivity of relaxing those specifications. This information will allow turbine manufacturers to set realistic specifications and decrease manufacturing costs while retaining turbine performance.

Objectives

The objectives of this task are to develop advanced techniques for characterizing the flow near the blades of an operating WECS, obtain a better understanding of that flowfield, and determine the effects of blade profile tolerance and blade surface finish on blade performance.

Approach

This task comprises the following efforts:

1. Reactivate the Sensor Calibration Laboratory at SNL and adapt/develop instrumentation for use in WECS flow field characterization, pursuing cooperative efforts with U.S. industry. Priority will be placed on obtaining boundary layer and wake information.
2. Use this instrumentation to characterize the flow in the immediate vicinity of two-dimensional oscillating airfoils in wind tunnel environments and adapt it to field use on a WECS.
3. Develop a non-contact measuring system to accurately and quickly determine the profile and surface finish of WECS airfoils. Determine the 2-d wind-tunnel performance of several wind-farm airfoils and evaluate the effect on performance of changes in the profile and surface finishes of the airfoils.

Output

The outputs from this task will include:

1. New instrumentation that can be used by researchers in the wind industry.
2. A comprehensive database of the flowfield characteristics in the near vicinity of the blades on operating WECS that can be used to guide code development and to validate codes.
3. A quick and accurate blade measuring instrument which can be used by turbine operators and manufacturers for blade quality control, leading to improved blade performance.
4. Guidelines for realistic blade profile and surface finish specifications which will lead to lower blade costs.

TASK 1.3.1: WECS Structural Dynamics **Priority = 6**

Principal Investigator: P. S. Veers

FY94 Funding (Scenarios A/B/C): $200/200/500k

Cumulative Funding (Thru FY93): Unknown

PROJECT SUMMARY

Background

Over the years Sandia has developed a suite of computer analysis codes that predict structural behavior of wind turbines under successively more sophisticated loading conditions. As the level of complexity of the analysis increases, the size and computational demands of the codes also increase. Considerable effort has also been expended to automate the integration of aerodynamic loading into the structural response calculations. At the time of the development, the computer resources required to complete this level of detailed modeling was extensive, well beyond the reach of many wind industry members. While the capability of small computers has mushroomed, the cost has plummeted to the point where even the most sophisticated modeling is within the reach of all industry members. Attention is now turning to the adaptation of Sandia's suite of analysis codes to stand-alone application on computers already in the possession of the industry. Codes that are currently limited to a small set of machine configurations can be adapted to more general purpose applications. At the same time, attention must remain on validating and improving the codes to account for effects just now becoming well enough understood to be amenable to computer analysis. Cooperative efforts to evaluate analysis codes and bring industry members up to speed in their use must be pursued.

Objectives

Validate and document our current analytical capability to accurately determine the nature and magnitude of dynamic load effects on wind turbine structures while making the analysis capabilities accessible to the wind industry on affordable computer platforms.

Funding Level C: Important gaps in wind turbine structural analysis codes continue to exist. The enhanced funding level would permit Sandia to bring our documented world-class capabilities in structural analysis tool development to bear on horizontal axis wind turbine problems.

Approach

Continue basic research and refinement efforts to improve predictions of both mean and fluctuating turbine stresses. Computer analysis codes that currently use expensive commercial software will be made to run in stand-alone mode (without extensive additional software requirements) as appropriate. We will work with industry partners to validate and educate them to the existing state of the art in HAWT structural dynamics simulation (the ADAMS code).

Output

Structural response codes that will enable industry and researchers to more easily and accurately predict the mean and cyclic loads on a wind turbine, as well as control system effects, leading to improved designs, longer turbine lifetimes, improved controller performance and lower cost of energy.

TASK 1.3.2: Structural Reliability Analysis **Priority = 1**

Principal Investigator: P. S. Veers

FY94 Funding (Scenarios A/B/C: $300/300/300k

Cumulative Funding (Thru FY93): $400k

PROJECT SUMMARY

Background

The fatigue lives of components can be estimated with recently developed tools, such as the LIFE2 code, but the estimate is very sensitive to input variations and is therefore highly uncertain. A structural reliability analysis combines the inherent randomness and uncertainty in individual inputs to the fatigue life estimate into a probabilistic framework that produces a component reliability measure, while also estimating the relative importance of each input. This approach therefore casts the fatigue life prediction results into a more meaningful format for business decision making. The reliability of the wind turbine components can then be combined into a system reliability estimate. The final result is an estimate of the probability of failure of the WECS. The fatigue reliability of a wind turbine must be assessed before accurate economic forecasting can be done, especially for large-scale energy applications.

Objectives

Develop reliability analysis procedures that assess component fatigue and system reliability and identify important parameters for system performance enhancement and economic forecasting.

Approach

Existing reliability analysis tools will be used initially to calculate fatigue reliability for individual turbine components. Research has been initiated into methods of casting traditional inputs into a fatigue lifetime calculation in probabilistic format. The LIFE2 code, or a derivative thereof, will be tied to a reliability-code calculation with appropriate considerations given to defining probabilistic descriptions of input quantities. System reliability analysis techniques will then be developed. Finally, the system reliability measures will be combined with probabilistic cost and performance projections as an aid in economic decision making. Eventually, these individual turbine system measures may be used in the analysis of wind farm availability and production forecasts.

Output

Initial research will provide a methodology for producing fatigue reliability predictions in the wind turbine environment. A computer code that enables the industry to estimate component fatigue reliability will then be created, followed by an analysis procedure for determining wind turbine system and wind farm reliability and financial risk.

TASK 1.3.3: Vibration Analysis and Suppression **Priority =22**

Principal Investigator: P. S. Veers

FY94 Funding (Scenarios A/B/C): $0/0/300k

Cumulative Funding (Thru FY93): $400k

PROJECT SUMMARY

Background

Structural vibrations due to inherent turbulence in the wind is a primary source of fatigue damage, limiting the economic lifetimes of WECS. The understanding and suppression of these wind-driven vibrations is central to enhancing the structural performance of wind turbines. Testing techniques have been developed to determine the mode shapes, natural frequencies, and damping levels for stationary WECS of all sizes. Damping levels in turbine blades have been shown to be important, and have been measured in the laboratory. Only recently have we successfully measured damping during operation. Analytical predictions of aeroelastic damping, which are currently suspect because of the highly nonlinear nature of WECS aerodynamics, can now be critically evaluated. It is now also possible, through a combination of test and analysis, to evaluate the feasibility of using damping enhancement procedures to reduce the dynamic response of wind turbines with the intent of reducing costs and extending fatigue life.

Objectives

Validate the accuracy of structural dynamic analyses and both structural and aeroelastic damping estimates. Find damping enhancement procedures to suppress turbulence driven vibrations.

Approach

Modal testing techniques for the rotating 34-m VAWT Test Bed will be developed and results compared with the results predicted by the existing finite-element codes and models. These results will be used to evaluate aeroelastic modeling capabilities and guide further developments of the analytical codes. Our new method of extracting the total damping during operation will be exercised extensively on existing data sets to lay out the fundamental damping behavior of wind turbines under a wide variety of operating conditions. Methods of inducing higher blade damping levels will be investigated with the intent of suppressing turbulence-induced vibrations and extending turbine fatigue life.

Output

A database of damping measurements will be produced to improve understanding of aeroelastic effects. A better understanding of how to model wind turbine structural/aerodynamic interactions will result. Methods of suppressing damaging turbulence-induced vibrations will be developed.

TASK 1.3.4: Structural Parameter Estimation **Priority = 8**

Principal Investigator: P. S. Veers

FY94 Funding (Scenarios A/B/C): $200/200/200k

Cumulative Funding (Thru FY93): $50k

PROJECT SUMMARY

Background

Computer models of WECS structures can only be useful tools for product development and improvement if they accurately model reflect the structural mass and stiffness properties. In the past, models of turbines with metal blades have been very accurate, but many current designs have fiberglass composite blades with uncertain material properties. The hand lay-up process used to manufacture many HAWT blades creates additional uncertainty in the fabricated blade structural properties. Modal testing can determine the dynamic properties of a structure. System identification techniques, which have been under development at Sandia for the past five years, are now at a point where modal test results can be used to automatically update a finite element model. In addition, modal test results have been shown to be applicable to quality assurance and damage detection in structures. A multiple-funding-source program in structural health monitoring, recently started at Sandia, addresses these issues. We will cooperate in this technology development by supplying a ready application (and hardware) from the wind industry through existing cooperative arrangements, thus making use of the highly leveraged research effort and tying the work to industry development activities.

Objectives

Adapt existing Sandia tools to automatically update WECS structural models with modal test results to address the problem of composite blades with uncertain material and structural properties and general uncertainty in structural modeling. Create an improved approach to WECS quality assurance and damage detection.

Approach

The methodology and test hardware for the task are under development. Software will be written to handle the specific case of a HAWT finite element model with modal test results for a single blade. Damage detection methods will be evaluated by conducting fatigue tests on wind turbine blade parts while implementing a suite of health monitoring technologies. Eventually, the entire system model will be refined with similar whole system modal testing and parameter estimation.

Output

(1) A software package will automatically update a WECS finite element structural model to account for uncertainties in material and structural properties based on modal tests. (2) A method for monitoring the adequacy of structures in the factory (quality assurance) and in the field (damage detection) will be created.

TASK 1.3.5: Composite Microdesign Tool **Priority = 13**

Principal Investigator: T.D. Ashwill

FY94 Funding (Scenarios A/B/C): $0/200/200k

Cumulative Funding (Thru FY93): $50k

PROJECT SUMMARY

Background
Wind turbine designers have often in the past not designed their composite blades, but relied on blade manufacturers to do so. The blade manufacturers often work with their own consultants to design blades by closely-held design techniques. It has become apparent that a need exists for an easy-to-use design tool that will allow turbine manufacturers/designers to perform in-house preliminary design and analysis of composite blades.

Objectives
To produce a composite design tool that is based on a readily available PC-based finite element code that will also perform composite structural analysis.

Approach
Identify various PC-based finite element codes that have options to perform composite design and analysis. Purchase one of these codes and develop a preprocessor to help the engineer in the turbine blade design process. Develop a library of composite and wood materials that can be used for the laminate schedule. Develop examples showing how to use the tool and document. Examples of uses would include:

- Show how to automatically and quickly create the geometry of a typical HAWT blade.
- Show how to create a blade's laminate architecture.
- Subject the newly created blade to a frequency and ultimate strength analysis.

Advanced characteristics that would be incorporated include the capabilities to predict stress concentrations and buckling failures.

Output
A PC-based finite element design tool specifically tailored to the needs of wind turbine blade designers.

TASK 1.3.6: Advanced Fatigue Models **Priority = 10**

Principal Investigator: H. J. Sutherland

FY94 Funding (Scenarios A/B/C): $ 100/100/100k

Cumulative Funding (Thru FY93): $ 1960k

PROJECT SUMMARY

Background

The operational experiences of the wind industry in California have shown that WECS components (primarily blades) were failing at unexpectedly high rates. This realization led to the development and distribution to industry of the LIFE code, a damage accumulation model for VAWT components, in the late 1980s. A generalized numerical framework (the LIFE2 code) for the fatigue and/or fracture analysis of WECS' components has been completed. The current version of the code, 3.05, has been updated by the addition of a rainflow counting algorithm and a frequency synthesis module. The rainflow counter permits the analysis of time-domain data, and the frequency synthesis module permits the analysis of frequency-domain data. The code and a four-volume reference manual have been released to industry. Currently, the LIFE2 code is being evaluated by several U.S. wind turbine companies, wind farm operators, consultants and researchers. To further assist the U.S. wind turbine community in the use of this code, a short course on its use has been presented. Based on the evaluations received to date, the code has been updated to reflect suggested changes, additions and corrections to the code.

Objective

Develop an analytical capability to determine the lifetime of turbine components, given the time varying loads (stresses) on the component.

Approach

Investigate the use of advanced material and damage models for the fatigue analysis of WECS, compare the relative strengths and weaknesses of the advanced models with the linear fatigue models currently in use, and proceed to develop the technique with the most promise. Develop the capability to realistically estimate the service life of WECS. This capability will use, and be validated against, the results of long-term fatigue testing in the lab and in field experiments, and will be used to analyze current design practices and operating strategies from a fatigue basis, assess the relative merit of industry design concepts, and conduct comparative studies of control algorithms. To assist the U.S. wind turbine community in the use of this code, short courses on its use will be presented to them as they deem necessary.

Output

A comprehensive fatigue analysis capability, with U.S. turbine personnel trained in its use, which can be used to assess the impacts of system and component design concepts and operating strategy on machine reliability and cost.

TASK 1.3.7: Composites Fatigue **Priority = 2**

Principal Investigator: H. J. Sutherland

FY94 Funding (Scenarios A/B/C): $ 200/200/400k

Cumulative Funding (Thru FY93): $1150k

PROJECT SUMMARY

Background

In California, approximately 80 percent of all WECs are equipped with fiberglass composite blades. As these blades are now experiencing fatigue failures due to cyclic loading, a fatigue analysis capability for composite materials is required. Initial testing has been completed on typical U.S. composite blade materials. The high cycle fatigue testing of composite materials requires the use of servo-controlled test frames. A typical test to 10^8 cycles will run for 100 days, and will consume 10 percent of the design life of the test frame's ram and servo-valves. Thus, the experimental program is severely limited by machine time. To help overcome this limitation on testing time, the test facilities at MSU have been upgraded.

Objectives

Develop an analytical capability to determine the lifetime of typical U.S. composite blade materials that is appropriate for the load spectrum encountered by wind turbines. Develop the constitutive relations for a representative set of WECS composite materials. Develop high-frequency techniques for fatigue testing of composite coupons. The constitutive research has a direct tie to the NREL composite test program to insure a synergistic program.

Approach

Using existing analyses, develop an analytical description for the fatigue behavior of fiberglass composite materials used in a WECS environment. Initial studies will concentrate on typical U.S. blade materials. The material tests will be conducted with Montana State University (MSU) as a major subcontractor. To speed test times, a small-coupon testing technique is being developed. Samples are being supplied by several major U.S. blade manufactures. Additional funds are needed to refurbish testing machines being consumed by the high-cycle characterization of composite blade materials. Implement the constitutive relations into the WECS fatigue analysis code LIFE2. Develop the necessary constitutive equations, using laboratory experiments, for representative fiberglass composites (when not available elsewhere). Validate constitutive descriptions and analysis techniques using field data. This program is being conducted in coordination with the NREL full-blade and blade component fatigue testing program.

Output

A comprehensive fatigue analysis capability for composite materials subjected to wind turbine loads.

TASK 1.3.8: Joint Bonding Research **Priority = 7**

Principal Investigator: H. J. Sutherland

FY94 Funding (Scenarios A/B/C): $ 200/200/200k

Cumulative Funding (Thru FY93): $ 350k

PROJECT SUMMARY

Background
In California, approximately 80 percent of all WECs are equipped with fiberglass composite blades. A typical failure mechanism for these blades is the fatigue failure of the bonded root joints. A fatigue analysis capability for bonded joints in composite materials is required. Initial studies have developed fabrication techniques and the testing of cylindrical joints.

Objectives
Develop an analytical capability to determine the lifetime of bonded joints in composite blade materials that is appropriate for the load spectrum encountered by wind turbines. Develop the constitutive relations for a representative set of WECS joints in typical U.S. composite blade materials. Develop high speed testing techniques for typical bonded structures.

Approach
Use existing analyses, develop an analytical description for the fatigue behavior of bonded joints in fiberglass composite materials used in a WECS environment. With the completion of the initial test series, the experimental study is being developed around typical U. S. blade materials. A tie with a U.S. blade manufacturer has been established. Develop the necessary constitutive equations, using laboratory experiments, for representative joints in fiberglass composites. Validate constitutive descriptions and analysis techniques using field data. Implement analysis techniques into a fatigue analysis code for use by industry. An addition of a bonded joint research project with an appropriate university to develop a fatigue characterization of typical adhesives used by U.S. blade manufactures is being considered for this project.

Output
A comprehensive fatigue analysis capability for bonded joints in composite materials subjected to wind turbine loads.

TASK 1.3.9.A: Acoustic NDT/Inspection **Priority = 5**

Principal Investigator: H. J. Sutherland

FY94 Funding (Scenarios A/B/C): $ 200/200/200k

Cumulative Funding (Thru FY93): $ 300

PROJECT SUMMARY

Background
The California experience has shown that WECS blades are failing at unexpectedly high rates. These failures can be traced, in part, to poor quality control of the blade manufacturing process. To identify poorly manufactured blades and to inspect used blades for accumulated damage in the WECS manufacturing environment requires the use and adaptation of commercially available wide-area Non-Destructive Testing (NDT) techniques that inspect large WECS components quickly. This approach to inspection permits the operator to identify substandard or highly damaged components with a minimum disruption.

Objectives
Adapt existing wide-area NDT techniques to the quality control of WECS blades as they are being manufactured. Adapt wide-area NDT techniques to the in-service inspection of WECS blades for accumulated damage and incipient failure.

Approach
Use typical wide-area NDT techniques to inspect typical blades and blade structures. The techniques will be tried first in a laboratory environment (a proof-of-concept experiment) and then proceed to the manufacturing environment. Acoustic emissions and coherent optical techniques have been tested in a proof-of-concept test program being conducted by NREL in their full-blade test facility. Both demonstrated the capability to inspect a whole blade and to find manufacturing flaws and areas of damage. Additional wide-area NDT techniques will be investigated. To insure that the evaluation and adaptation of the NDT techniques to the WECS environment is addressing the needs of the U.S. wind industry, a collaborative program is being developed. The program will emphasize quality control and inspection during the manufacturing process. This program has a direct tie at Sandia to the FAA Aging Aircraft Program.

Output
Wide-area NDT techniques for rapid inspection of wind turbine components for both manufacturing and in-service environments.

TASK 1.3.9.B: Localized Inspection/Field Inspection **Priority = 5**

Principal Investigator: H. J. Sutherland

FY94 Funding (Scenarios A/B/C): $ 000/200/400k

Cumulative Funding (Thru FY93): $ 000 (Previous Funding Under 1.3.8 and 1.3.9.A)

PROJECT SUMMARY

Background
The use of localized Non-Destructive Testing (NDT) techniques to determine the extent of known flaws and damage has been used extensively in the aircraft industry to define the cost/benefit ratio for fixing a flawed or damaged component. When used with wide-area NDT techniques, localized techniques provide detailed descriptions of flaws and they permit the inspection of small areas within large components that are not inspected by global techniques. The in-service inspection of wind turbine components for accumulated damage (and incipient failure) require the evaluation and adaptation of both localized and wide-area NDT techniques to the WECS field environment.

Objectives
Use localized NDT techniques to quantity flaws and damage in WECS components. Adapt existing NDT techniques to the in-service inspection of WECS components for accumulated damage and incipient failure.

Approach
Use of state-of-the-art localized NDT techniques to inspect known flaw structures in a WECS component in a laboratory environment. Acoustic wave techniques have been used successfully in a laboratory environment to characterize typical, WECS bonded joints by mapping bond thickness, voids and delaminations. Expand these laboratory demonstrations to include other promising localized inspection techniques. Use typical NDT techniques to inspect typical in-service blades and blade structures. The techniques will be tried first in a laboratory environment (a proof-of-concept experiment) and then proceed to field demonstrations. Based on these results, commercial apparatus will be evaluated in a laboratory and a field environment. To insure that the evaluation and adaptation of the NDT techniques to the WECS environment is addressing the needs of the U.S. wind industry, a collaborative program needs to be developed. The program will emphasize the identification and tracking of accumulated material damage in in-service components. This program has a direct tie at Sandia to the FAA Aging Aircraft Program.

Output
NDT techniques for quality control and inspection of wind turbine components for both manufacturing and in-service environments.

TASK 1.4.1: Windfarm Expert Systems **Priority = 12**

Principal Investigator: **L. L. Schluter**

FY94 Funding (Scenarios A/B/C): $50/50/50k

Cumulative Funding (Through FY93): $400k

PROJECT SUMMARY

Background

Many windfarm Operation and Maintenance (O&M) related procedures are ideally suited for expert system applications. Significant cost savings may be realized by incorporating expert systems in the daily operations of a windfarm. By collaborating with industry, several areas where an expert system can lower windfarm operators' O&M costs have been identified. One such area is aiding field maintenance teams with the troubleshooting procedure of faulty wind turbines. An expert system has been developed and implemented in this area and is currently being evaluated by industry.

Objectives

By collaborating with industry, investigate the potential benefits of expert systems that address O&M issues. Develop and implement expert systems in areas that our investigation finds to be appropriate applications for expert systems.

Approach

The two main tasks in developing an expert system have been accomplished. The first task was to identify areas where expert systems are applicable and feasible. Once an area was identified as being appropriate, an expert system was developed and implemented. By collaborating with industry an expert system that aids in the troubleshooting process of a faulty wind turbine has been implemented and is currently being evaluated. Collaboration with industry will continue with a focus on improving and documenting the existing expert system.

Output

Expert systems that will aid windfarm operators in lowering the cost of energy produced by Wind Energy Conversion Systems by optimizing their O&M related procedures.

TASK 1.4.2: WECS Advanced Controls **Priority = 4**

Principal Investigator: L. L. Schluter

FY94 Funding (Scenarios A/B/C): $200/200/200k

Cumulative Funding (Through FY93): $200k

PROJECT SUMMARY

Background
Current research involving control theory considers steady-state and transient operations, variable speed operations, and high wind survivability, and is based on classical control logic. No capability exists to take into account individual machine performance variations or array subgroup variations in a windfarm. Such factors as siting effects (including farm-to-farm and local terrain variabilities) and array effects (including wakes and power depletion) can significantly impact machine performance. The next generation of control algorithms will incorporate fuzzy logic, adaptive controls, and expert systems to achieve smoother and more efficient operation.

Objectives
To develop advanced control strategies that incorporate fuzzy logic, adaptive controls, and expert systems that will increase both fatigue lifetime and energy capture of a wind energy conversion system.

Approach
In collaboration with industry, use the results from current controls research and the field experience of windfarm operators to investigate advanced control concepts. Advanced control concepts will include the use of fuzzy logic, adaptive controls, and expert systems. Using independent variables such as wind speed and direction, critical turbine stresses and local turbulence intensity, determine advanced control strategies that will lead to lower energy costs through increased energy capture, component lifetimes and/or decreased O&M costs. An Advanced Control Simulator will also be developed to simulate the advanced control strategies and compare them against conventional control strategies. Implement the advanced control strategies on the Sandia 34-meter Test Bed to determine the amount of improvement in fatigue lifetime and energy capture that can be expected. In collaboration with industry, implement the advanced control strategies on individual machines and array subgroups within windfarms.

Output
Advanced control systems, including both specialized software and low-cost microprocessors, that will enable windfarm operators to increase energy capture, component lifetimes, and/or decrease O&M costs.

TASK 1.4.3: Field Testing/Test Bed/Power Quality **Priority = 15**

Principal Investigator: M. A. Rumsey

FY94 Funding (Scenarios A/B/C): $ 0/100/100k

Cumulative Funding (Thru FY93): $ 2425k

PROJECT SUMMARY

Background
A 34-m diameter VAWT Test Bed has been designed, fabricated and constructed, with final assembly and first turn achieved in FY88. Initial testing has defined mechanical and electrical baseline conditions.

This machine incorporates an advanced airfoil and innovative structural features. It is rated at 500 kW, a size of great interest to utilities. The data acquisition and analysis system has successfully demonstrated its capabilities.

Objectives
Develop and apply data acquisition and reduction techniques to acquire aerodynamic and structural dynamic data to validate current analysis tools. Develop control algorithms for operating in constant-speed and variable-speed modes and evaluate the effects of those algorithms on energy capture and fatigue life. Evaluate the power quality of a variable-speed generator system on a "soft" radial grid.

Approach
Supporting research for the VAWT Test Bed includes the following activities:
- Collection of basic performance data to define baseline conditions in a variable-speed environment.
- Integration of test plans and procedures.
- Coordination of test schedules and site utilization.
- Development of general data acquisition and analysis algorithms required for the more complex operating conditions.

Output
Basic Test Bed performance data for a variety of operating conditions and wind speeds that are used to support and validate Sandia's aerodynamics, structural dynamics, fatigue and controls research.

TASK 1.4.4: Fuzzy Control Applications **Priority = 16**

Principal Investigator: L. L. Schluter

FY94 Funding (Scenarios A/B/C): $0/100/100k

Cumulative Funding (Through FY93): (Formerly included in 1.4.1 and 1.4.2)

Background

As wind turbines become more complex, control algorithms and control hardware must become more sophisticated in order to operate the turbines as efficiently as possible. Control algorithms and hardware will need to incorporate concepts such as expert systems and fuzzy control logic not only on individual turbines but also in supervisor control systems for wind farms. While work is ongoing developing supervisor control systems for wind farms, a need exists to develop an advanced wind turbine controller. The controller should have the capability to incorporate rule based algorithms and have the ability to be remotely programmed by a supervisory controller. While the advanced controller needs to be more sophisticated, it also needs to be designed so that maintenance on the controller can be easily accomplished by the field maintenance engineer.

Objectives

To develop and design an advanced wind turbine controller that incorporates advanced control concepts such as expert systems and fuzzy logic.

Approach

In collaboration with industry, use the results from current controls research and the field experience of windfarm operators to investigate and design an advanced wind turbine controller. The controller will incorporate hardware that is capable of taking advantage of expert system and fuzzy control benefits. A key focus will be to design a controller that can be easily maintained by field maintenance personnel.

Output

An advanced wind turbine controller capable of using expert system and fuzzy control methods that can be easily maintained by field maintenance personnel.

TASK 1.4.5: WECS System Performance Models **Priority = 17**

Principal Investigator: H. M. Dodd

FY94 Funding (Scenarios A/B/C): $ 0/50/50k

Cumulative Funding (Thru FY93): $280k

PROJECT SUMMARY

Background

Over ten years ago Sandia developed a costing design code, ECON16, which was specifically tailored to evaluate VAWT configurations. ECON16 played a significant role in helping define the VAWT configuration leading to the development of over 500 commercial machines which continue to operate successfully today. In the late 1980s test results from the advanced DOE/Sandia VAWT Test Bed showed significant promise to improve on first generation VAWT cost of energy. Simulation capabilities were developed that enabled performance comparisons to be made between this technology and other existing and proposed WECS technologies. More recently Sandia provided extensive input to the interlaboratory NES effort. Finally, in FY93 Sandia and NREL cooperated in an update study that projected wind technology trends and costs into the early 21st century.

Objectives

The objective of this program is to develop Wind Energy Conversion System (WECS) performance/cost models that permit the evaluation of the effects of specific technology improvements as well as the effects of non-technical factors on system levelized cost of energy .

Approach

Through cooperative processes with NREL, available data and projections involving technical or economic improvements and policy options will be combined in a single model to establish relative impacts and sensitivities.

Output

The final output will be a model covering technical performance, economic optimization and national impact estimates for wind energy. This model will help bridge the gap between the applied research efforts on the one hand and the wind industry decision-maker on the other so that proper utilization of technology advances can be achieved.

TASK 1.4.6: Forecasting/Controls **Priority = 24**

Principal Investigator: L. L. Schluter

FY94 Funding (Scenarios A/B/C): $0/0/200k

Cumulative Funding (Through FY93): New Start

Background

As new windfarms start to be developed across the country, methods of accurately forecasting the availability of wind energy conversion systems (WECS) as well as the power needs of a utility will be of great benefit. Incorporating the forecasts into the supervisory control system of a windfarm will greatly enhance a utility's outlook on the potential of WECS impacting the utility's power production requirements.

Objectives

To develop methods that accurately forecast both the availability of WECS and the power needs of a utility for the next 24 to 48 hour period.

Approach

This project will proceed in two phases. First, by collaborating with both utilities and industry, methods that will accurately forecast the availability of WECS within a windfarm and the power needs of the utility for the next 24 to 48 hour period will be developed. Once these methods are known, they will be implemented by incorporating them within windfarm supervisory control systems.

Output

Windfarm supervisory control methods that forecast the availability of windfarm WECS and the power needs of a utility and adjust the power output of the windfarm accordingly.

TASK 2.1.1: Utility Industry Support **Priority = 21**

Principal Investigator: H. M. Dodd

FY94 Funding (Scenarios A/B/C): $ 0/0/200k

Cumulative Funding (Thru FY93): New Start

PROJECT SUMMARY

Background
The historical approach within the DOE to involving industry in any renewable energy technology has been to "sell" each technology as a single solution to a particular problem. This has often led to undesirable competition among technologies, and perceptions that DOE Laboratories were unilaterally setting program directions. In the electric utility industry wind has been identified as a leading candidate for a bulk generation source, and the current outlook is very promising. However, the DOE goal should be to work with the private sector to provide the most cost-effective (and integrated) solutions. These solutions must be perceived as arising from an unbiased process that objectively represents all potential contributors.

Objectives
This task seeks to provide wind technology representation to a fully integrated team involving all renewable energy technology development programs. This team will cut across technologies and Laboratories so that U.S. industry can access a single point of contact and provide the necessary market pull and private sector leveraging. This will create environments where renewables can compete fairly for their appropriate roles.

Approach
Through a single Program Development Office, Sandia will connect all its renewables activities to:
- Integrate technology expertise through part-time, rotating staff/management assignments.
- Be Sandia's single point of contact to credibly represent wind, PV, solar thermal and geothermal to all external interfaces.
- Identify and evaluate all potential partnerships.
- Lead efforts to create appropriate partnerships involving industry and other government entities.

Output
This task will result in broad, renewable energy solutions to problems, while creating an awareness of current market situations in order to help guide future program directions. It will also result in improved cost-effectiveness within the DOE by producing fully coordinated design assistance efforts, a shared customer data base, cross-technology education for Labs' personnel and highly leveraged technology representation.

TASK 2.2.1: Wind Technology Applications Project **Priority = 19**

Principal Investigator: H. J. Sutherland

FY94 Funding (Scenarios A/B/C): $ 0/100/100k

Cumulative Funding (Thru FY93): $400k

PROJECT SUMMARY

Background

The Wind Technology Applications Project (WTAP) was initiated in FY92 by NREL to support efforts by U.S. industry to improve the performance of existing wind turbines. As a result of the competitively bid solicitation, FloWind Corporation of San Rafael, California, was one of several companies selected to design and demonstrate modifications to their commercial product. Because this product is a VAWT configuration and SNL has DOE reponsibility and expertise for this technology, the placing and oversight of the contract was transferred to us. The project was initiated in the last half of FY92 when a contract for $370k was formalized. Significant progress has been achieved, but FloWind personnel replacements and additions and significant design changes have occurred that have delayed completion of this effort.

Objectives

- To provide SNL technical and contract oversight support to ensure the successful completion of this contract.

Approach

SNL will maintain the involvement of its technical monitor (Principal Investigator) as well as providing necessary technical consulting activities to be sure that the best possible engineering practices are being followed to provide maximum probability of project success. No additional funding is being proposed for FloWind's activities (i.e., the contract has been delayed, but will still be completed within current contract amounts).

Output

FloWind will report its design changes and test results from two modified commercial VAWT turbines. This report is the final outstanding task under the WTAP contract.

TASK 2.3.1: Advanced Manufacturing **Priority = 20**

Principal Investigator: T.D. Ashwill

FY94 Funding (Scenarios A/B/C): $0/0/900k

Cumulative Funding (Thru FY93): New Start

PROJECT SUMMARY

Background

The reduction of component costs is paramount in attaining truly competitive utility-grade wind turbines. Breakthroughs in wind turbine manufacturing can significantly lower capital costs. Technical improvements in several areas can impact wind turbine manufacturing and include: composite design, advanced materials, structural design, systems integration, robotics, cost/performance tradeoffs, serviceability and inspectability, and airfoil design.

Objectives

Develop methodologies to lower the cost of manufacturing wind turbine components.

Approach

This project is currently divided into two phases. Phase I is designated as Integrated Rotor Analysis and Manufacturing (IRAM) and concentrates on ways to improve the manufacture of rotors and blades. After a period of information gathering, proposals will be solicited from existing and potential blade manufacturers on ways to improve manufacturing processes to lower costs and produce blades more efficiently. The winning solicitations will be funded in follow-on contracts awarded in 1994/95. Phase II, which will start in the 1995 time frame, is termed Integrated System Manufacturing (ISM) and will seek ways to impact manufacturing of non-rotor components and of the entire wind turbine system. Possible areas of improvement/development include tower manufacturing, integrated generator and transmission systems, ease-of-maintenance designs, and integrated brake systems.

Output

New and improved manufacturing techniques to lower the cost of wind turbines.

TASK 2.3.2: VAWT Product Improvement **Priority = 18**
Principal Investigator: D. E. Berg

FY94 Funding (Scenarios A/B/C): $0/200/200k

Cumulative Funding (Thru FY93): $760k (plus $360k in Work for Others funding from FloWind, Inc.)

PROJECT SUMMARY

Background
Sandia's long history with wind energy was originally based solely on VAWT technology, and that effort led to a successful commercialization activity in the early 1980s. As a result of Sandia's 17m research VAWT and the development of the 17m DOE/Alcoa Low Cost commercial prototypes, there are now over 500 VAWTs operating in California. During the mid-80s Sandia conducted a cooperative effort (called the COVAWT program) with the two fledgling companies attempting to market VAWT product lines. Technical and financial difficulties eventually led to the demise of one of those companies (VAWTPOWER) and Chapter 11 bankruptcy proceedings for the other (FloWind). In CY 1990, FloWind emerged from bankruptcy and Sandia simultaneously publicly announced plans to transfer the advanced technology demonstrated on the DOE/Sandia 34m Test Bed. The result is a cooperative activity, jointly funded by the DOE and FloWind, that has evaluated the status of their VAWT fleet and is currently investigating options to improve the performance of those 512 machines.

Objectives
The primary objective is to transfer DOE-developed capabilities to U.S. industry. Specifically, utilizing advances developed at Sandia and elsewhere, we seek to provide the performance and reliability improvements that can improve the cost effectiveness of the existing VAWT fleet.

Approach
Help FloWind Corporation of San Rafael, California, improve the reliability and performance of their existing turbines by making our relevant skills in aerodynamics, structural dynamics, fatigue, materials, controls and field testing available to assist them. In particular, Sandia will continue to provide the technical skills required to help FloWind implement design modifications to their current turbines in order to optimize windfarm revenues.

Output
Transfer of our advanced technologies to a U.S. wind energy industry partner to aid them in maintaining economic competitiveness of a U.S. product.

TASK 2.4.1: Wind Design Assistance Center (DAC) **Priority = 14**

Principal Investigator: M. M. Harcourt

FY94 Funding (Scenarios A/B/C): $0/100/200k

Cumulative Funding (Thru FY93): $200k

PROJECT SUMMARY

Background

The Sandia DAC has been providing renewable energy technical and educational assistance to organizations developing renewable energy technology-based projects in the international arena for some time. These efforts, supported by DOE OSEC and DOE OTA, have frequently included support of wind project resource assessment, site evaluation and training on small wind electric systems in several stand-alone and hybrid applications. Late in FY92 the DAC received funding from OREC which enabled it to expand its organic wind capabilities and to accelerate its market development activities for wind projects.

Objectives

The objectives of this task are to provide an increased emphasis on small wind systems in the project identification, development, evaluation and implementation efforts under way worldwide in support of DOE/OSEC and CORECT program goals. Particular importance will be placed on development of wind-related training and education materials, evaluation of fielded wind systems and on wind resource assessment facilitation. Our main objective is to totally integrate wind into our RE energy services for systems ranging from small stand-alones to village power hybrids.

Approach

The objectives will be obtained by factoring wind as an option into each project evaluation, compilation of wind resource data, education of project decision makers on the benefits and characteristics of wind systems, and by collaborating with ongoing Balance of Systems efforts at Sandia to include wind as a component in hybrid power processing schemes. Our international priority will be to Latin America and the Caribbean, with a strong secondary effort in the Pacific Rim. We will work closely with the U.S. small wind industry, US ECRE and DOE OREC to ensure changing customer priorities and emphasis are reflected, and to facilitate the development of international markets for U.S. industry.

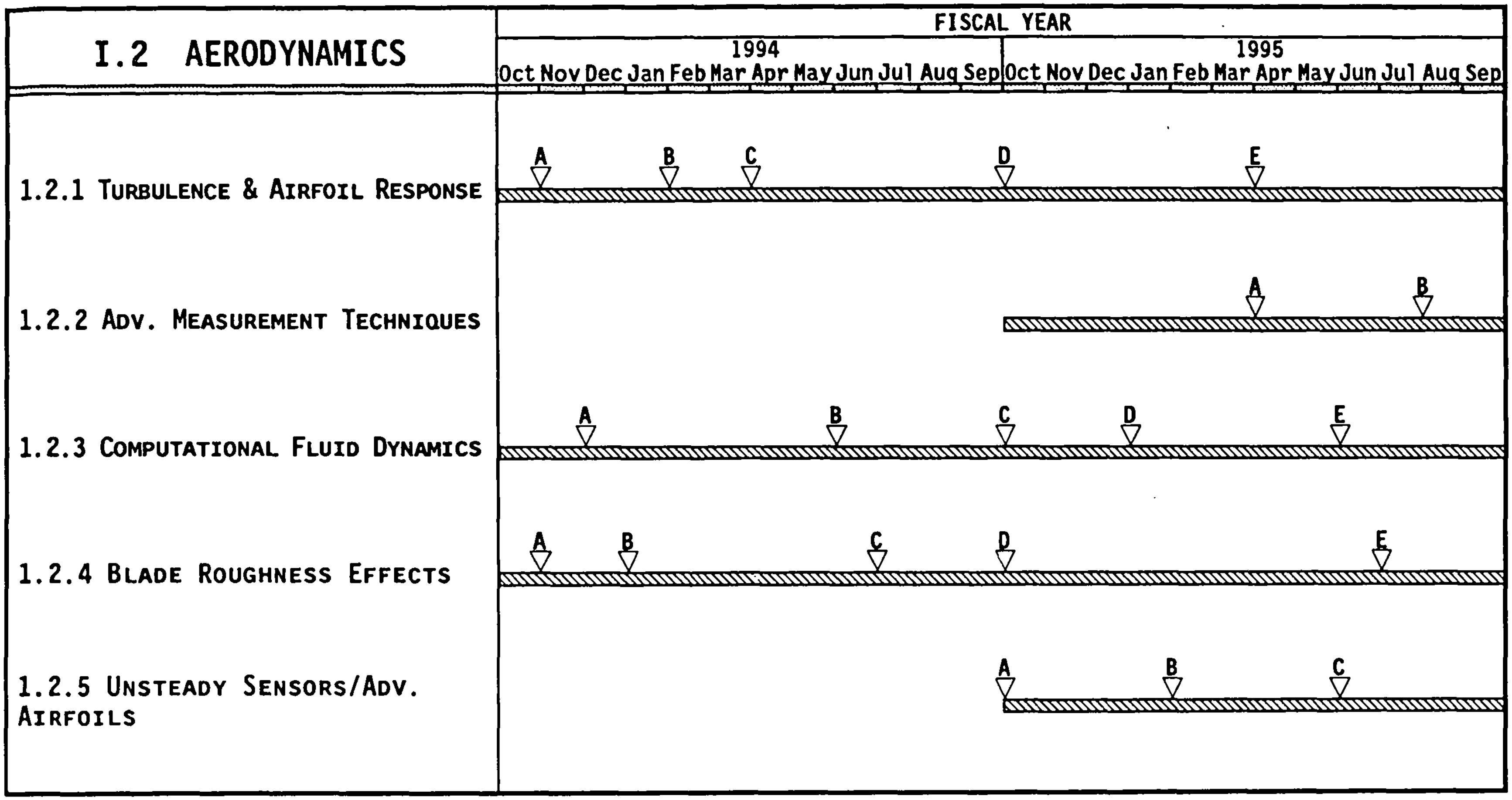
Output

The output of this task will be the presentation of workshops with a wind component, the identification and evaluation of projects with a wind component, facilitation of the dissemination of wind resource data, and the evaluation of installed wind systems.

APPENDIX C

Task Milestone Charts

I. APPLIED RESEARCH



1.2.1 Turbulence & Airfoil Response
- A=FDM Array Capability Incorp'd
- B=Improved Dynamic Stall Model
- C=FDM Initial Validation
- D=Improved FDM Graphics
- E=FDM Array Wake Validation

1.2.2 Adv. Measurement Techniques
- A=Test Plan Defined
- B=Wind Tunnel Testing

1.2.3 Computational Fluid Dynamics
- A=Unsteady Sol'n for SNL 18/50
- B=Airfoil Modifier Study
- C=General Unsteady Sol'n
- D=Turbulence Model in Ecole Code
- E=3-D Version of Ecole Code

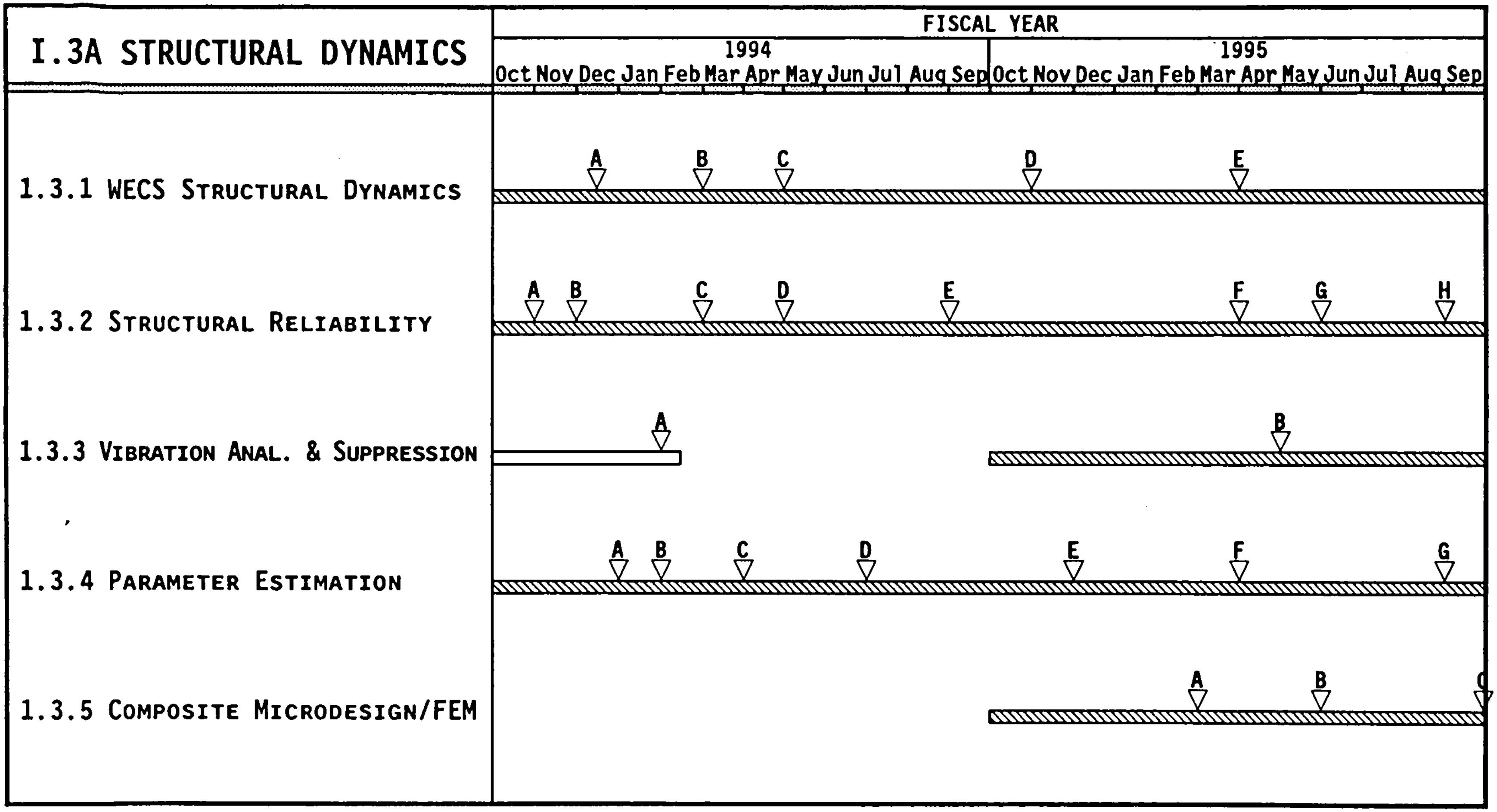
1.2.4 Blade Roughness Effects
- A=Initial Blades Scanned
- B=Comprehensive Plan Defined
- C=Roughness Parameters Defined
- D=1st Phase Windfarm Data
- E=Roughness Database Available

1.2.5 Unsteady Sensors/Adv. Airfoils
- A=Flow Modifiers Defined
- B=Flow Modifiers Installed
- C=Flow Modifiers Test Report

Assumes FY94 Applied Research BA = $2.15M

A94AERO 10-01-93

I. APPLIED RESEARCH (CONT'D): 3. STRUCTURES & FATIGUE



1.3.1 WECS Structural Dynamics
- A=Industry Model Validation
- B=VAWT SDS Documentation
- C=Industry ADAMS Application
- D=Industry Needs Assessment
- E=ADAMS Assessment

1.3.2 Structural Reliability
- A=Tail-Fitting Routine Complete
- B=FAROW User's Manual
- C=Tail-Fitting Report Published
- D=FAROW Version 1.1
- E=Fatigue Reliability Report
- F=Industry Reliability Short Course
- G=System Reliability Prelim Assessment
- H=FAROW Version 2.0

1.3.3 Vibration Anal. & Suppression
- A=HAWT Rotor Damping Report
- B=Damping Mat'ls & Devices Evaluated

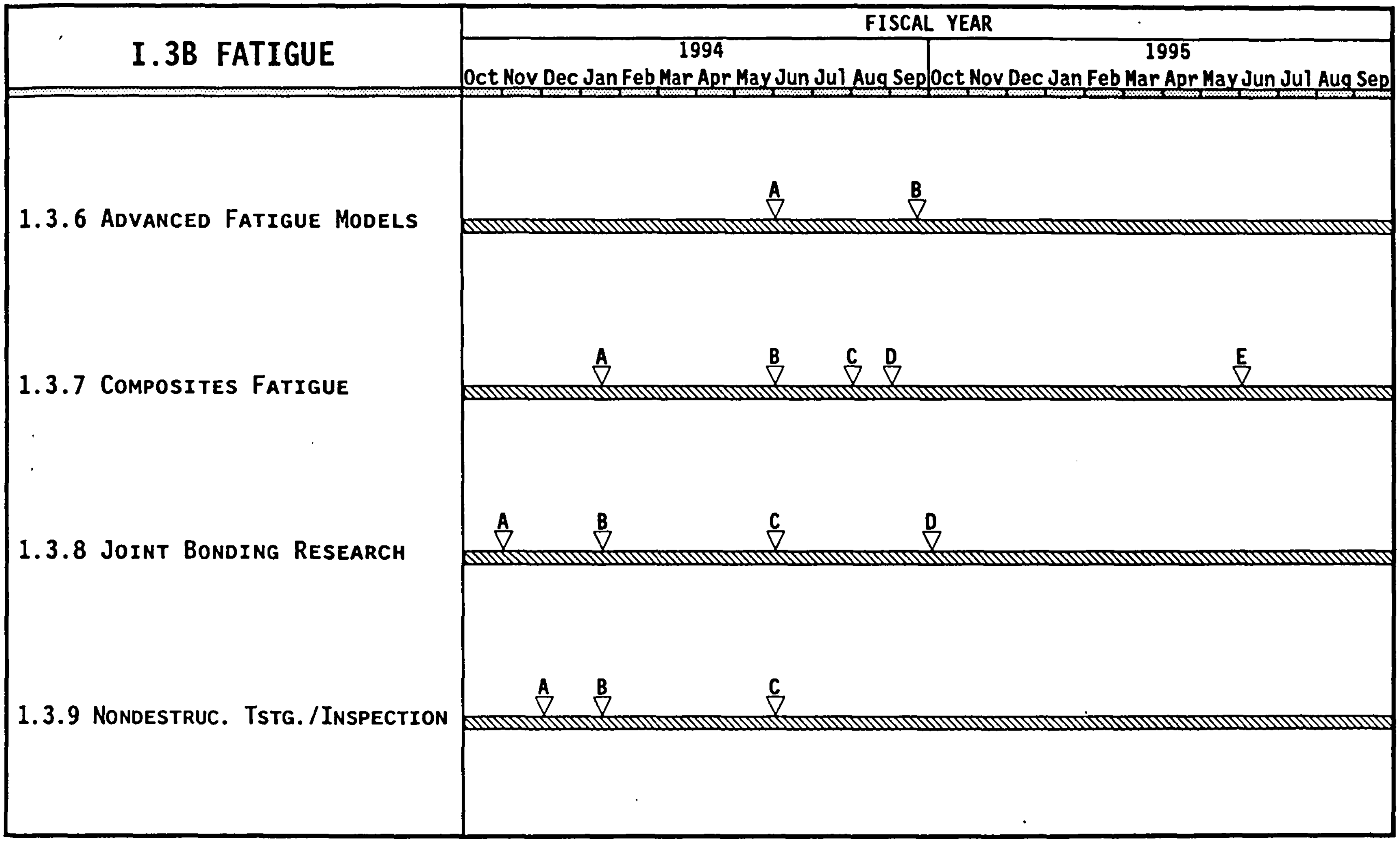
1.3.4 Parameter Estimation
- A=Rotor ID Trial
- B=Start Blade Piece Fatigue Test
- C=Blade Piece I.D. Report
- D=Blade Piece Damage Detection
- E=Component I.D. Software
- F=Component I.D. Report
- G=System Damage Detection

1.3.5 Composite Microdesign/FEM
- A=PC-Based Composite Codes Selected
- B=Industry/Consultant Partners ID'd
- C=HAWT Blade Design Preprocessor Compl.

Assumes FY94 Applied Research BA = $2.15M

A94S&F1 10-01-93

I. APPLIED RESEARCH: 3. STRUCTURES & FATIGUE (CONT'D)

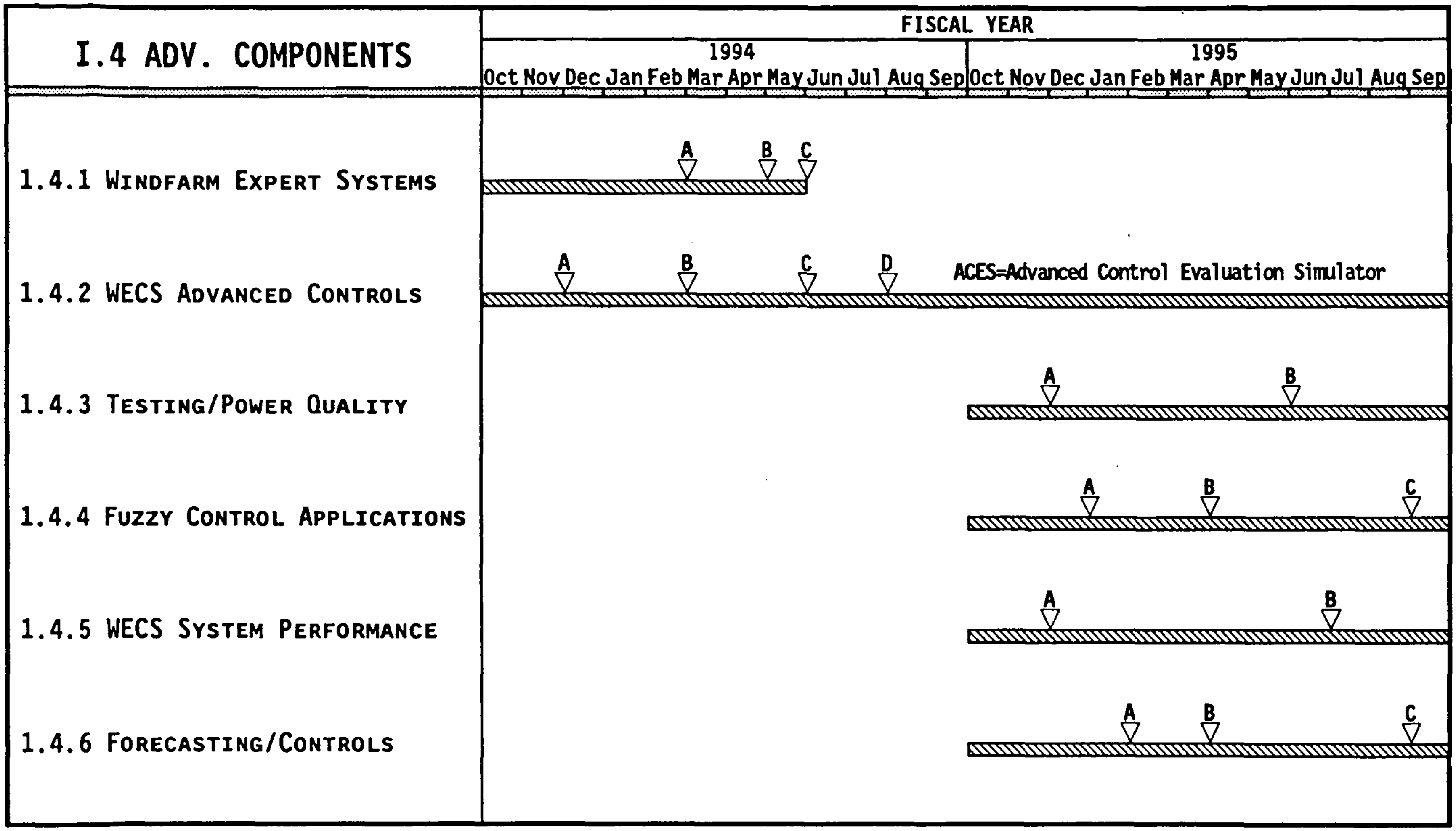


1.3.6 Advanced Fatigue Models
A=Gear Model in LIFE2
B=Updated LIFE2 Documented
1.3.7 Composites Fatigue
A=Ply Termination Results Reported
B=1st High-Speed Specimen Results
C=Long-Term Test Mat'ls Report
D=Ply Termination Constitutive Eq'n
E=High-Speed Specimen Validated
1.3.8 Joint Bonding Research
A=Begin Analysis of Industry Joint
B=Bond Joint Bending Report
C=Full-Scale Fatigue Test Complete
D=Industry Joint Analysis Complete
1.3.9 Nondestruc. Tstg./Inspection
A=Report on NREL Full Blade Test
B=Acoustic Emission Lab Test
C=Lab Inspection of Industry Joint

Assumes FY94 Applied Research BA = $2.15M

A94S&F2 10-01-93

I. APPLIED RESEARCH (CONT'D)



1.4.1 Windfarm Expert Systems
- A=Final Expert System Installed
- B=Final Report
- C=Task Complete

1.4.2 WECS Advanced Controls
- A=Expert System Incorp'd in ACES
- B=Fuzzy Logic Incorp'd in ACES
- C=Fuzzy Logic Validated
- D=Supervisory Control Implemented

1.4.3 Testing/Power Quality
- A=Follow-on Power Quality Tests w. SPS
- B=Power Quality Final Report

1.4.4 Fuzzy Control Applications
- A=Hardware Requirements Defined
- B=Hardware Design Complete
- C=Hardware Imlemented in Field

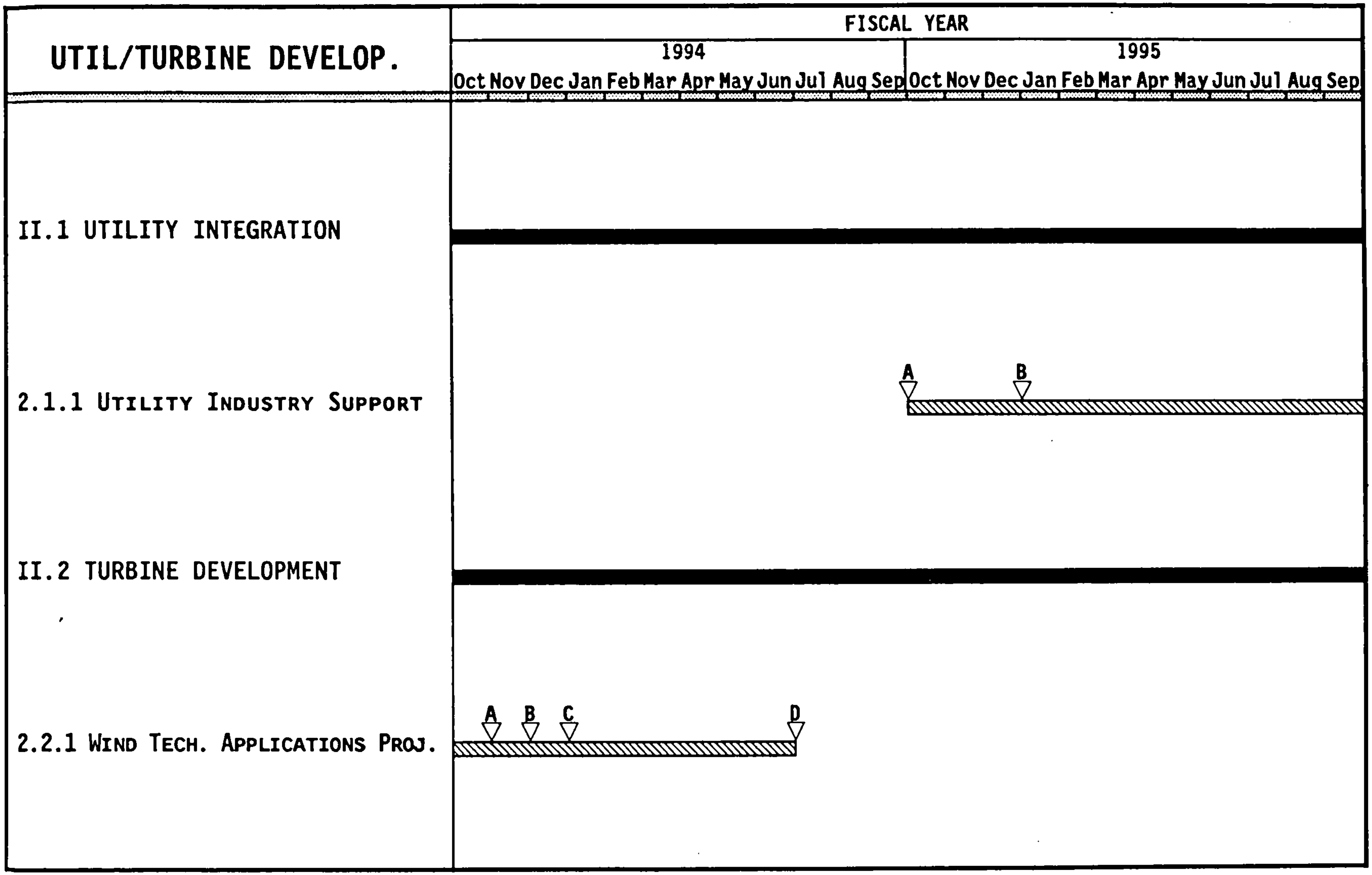
1.4.5 WECS System Performance
- A=Initiate Windfarm Comparative Study
- B=Preliminary Study Results

1.4.6 Forecasting/Controls
- A=System Requirements Defined
- B=Forecasting Implemented in ACES
- C=Forecasting Algorithms Validated

Assumes FY94 Applied Research BA = $2.15M

A94COMP 10-01-93

II. UTILITY & INDUSTRY PROGRAMS



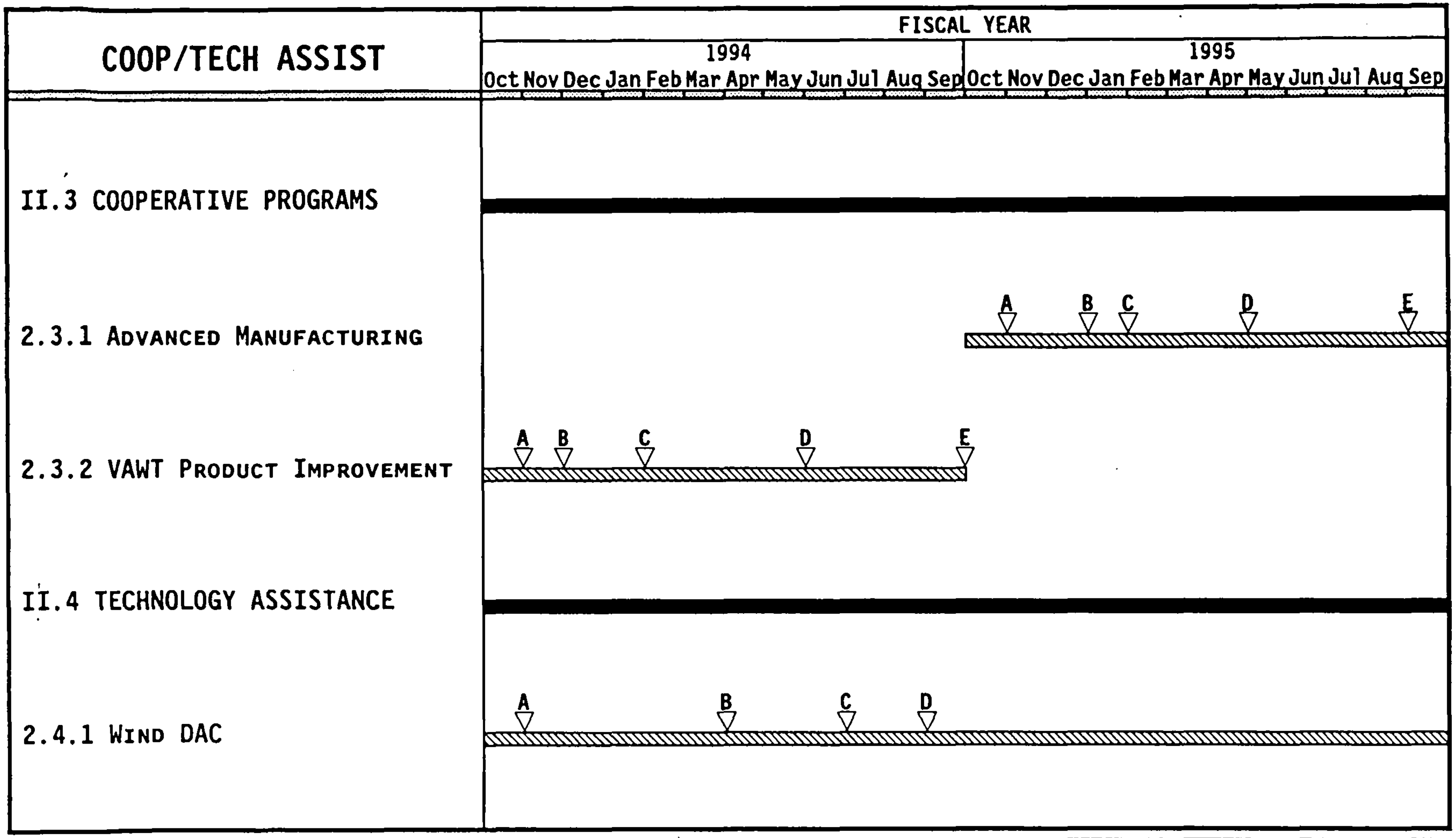
2.1.1 Utility Industry Support
A=Cross-cutting Team Established
B=ID of Utility Participant(s)

2.2.1 Wind Tech. Applications Proj.
A=Blades Delivered to Site
B=Turbine #1 Ready for Testing
C=Turbine #2 Ready for Testing
D=Final WTAP Report

Assumes FY94 Budget Scenario B for Key Area II

A94UI1 10-01-93

II. UTILITY & INDUSTRY PROGRAMS (CONT'D)



2.3.1 Advanced Manufacturing
- A=ID Current/Potential Players
- B=Needs Assessment Complete
- C=CBD Announcement
- D=Proposals Due
- E=1st Contract(s) Placed

2.3.2 VAWT Product Improvement
- A=SNL DAAS On Site & Operational
- B=SNL Structural Analysis of Final Design
- C=1st Data Set Complete & Analyzed
- D=Wake Effects Quantified
- E=SNL Analyses Final Report

2.4.1 Wind DAC
- A=PV/Wind Bolivia Waterpumping Workshop
- B=English/Spanish Training Manual (Incl. Wind)
- C=ID 2 Int'l RE Projects (Incl. Wind)
- D=Coord. Publ'n. of Int'l Wind Doc. (w. AWEA/NREL)

Assumes FY94 Budget Scenario B for Key Area II

A94UI2 10-01-93

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